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RECORDING AND ANALYSIS OF OPTICAL DATA FROM STRATOSPHERIC DYNAMICS EXPERIMENTS

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14 January 1978

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A program whose objective is the study of stratospheric winds and temperatures, and mass transport processes in the stratosphere and upper atmosphere, is described. These parameters are determined through reduction and analysis of photographs of sunlight-scattering chemical and smoke (particulate) tracers deposited from rockets. Computer programs implementing triangulation by vector and matrix → over

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methods were developed to measure three-dimensional smoke trail positions from multiple photographic projections of the trails. Horizontal winds and shears were derived from the transport of these trails.

FOREWORD

The work reported here consists of the application of photographic film reduction methods and computer analysis of digitized photographic data to the problem of determining the stratospheric wind field. This effort is a contribution to the continuing program of study of atmospheric processes through analysis of photographs of tracer materials conducted by the Composition Branch (LKD), Air Force Geophysics Laboratory (AFSC), Bedford, MA. Similar earlier work by the PhotoMetrics research group is described in Ref 3.

The authors wish to express their thanks to D. Gentile, who performed most of the photographic darkroom procedures and provided data reduction support, and C.C. Rice who also made important contributions to the studies described in this report. The continued encouragement and support of Dr. A.F. Quesada (Technical Monitor), Dr. R.E. Good, and K. Vickery of the LKD branch of AFGL is gratefully acknowledged. Special thanks is extended to R.O. Olsen Atmospheric Sciences Laboratory, USAEC, WSMR, N.M. for making Rawinsonde wind profiles available for comparison purposes.

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SECTION I

SUMMARY AND OVERVIEW

The objective of the program described here is the study of winds, wind shears, temperatures, and transport processes primarily by reduction of photographic observations of tracer chemical trails released from rockets in the stratospheric, mesospheric, and thermospheric regions of the atmosphere. PhotoMetrics participated in the photography of trail releases, and in the reduction, calibration, analysis and interpretation of optical data from atmospheric releases conducted by the LKD branch of the Air Force Geophysics Laboratory during 1977, and performed similar tasks on data from earlier field programs. Quantities measured are the time dependent trail positions, and winds and wind shears derivable from these positions.

The major portion of the work on this program was the development of computer algorithms to implement the triangulation methods contained in Ref 1 in a manner which would provide consistent trail position and velocity results. The principal application of these methods has been to stratospheric trails, with the goal of providing horizontal velocity profiles at a maximum vertical resolution of 10 meters. This effort is briefly summarized in Section III; it is pointed out that large volumes of data were generated during the course of the program which were presented immediately to the project scientists for evaluation and application. Examples of the use of these data may be found in references 6 and 7.

Photographic darkroom procedures and participation in field measurement programs are detailed in Section II. The brief description of film development and calibration procedures reviews material in References 3-5 and earlier PhotoMetrics reports on remote atmospheric sensing programs which they reference. Section IV presents conclusions and recommendations.

SECTION II

FIELD OPERATIONS AND SUPPORT TASKS

This section briefly describes calibration procedures, miscellaneous support tasks and field operations.

CALIBRATION PROCEDURES

Photographic records of chemical and smoke trails and puff releases deposited in the atmosphere may be utilized to study diffusion, atmospheric turbulence, winds and mass transport, species inventories, and reaction rates of release particles with ambient species. Most of these studies require that the films be photometrically calibrated and uniformly developed.

Photometric calibration is performed by placing density step tablets on the same film used to photograph the release. This is accomplished using a modified AFGL built uniform low brightness source with irradiance traceable to NBS standards. The typically 100 ft rolls of film are then developed by a strictly controlled procedure designed to produce uniform and consistent results. Detailed description of these procedures may be found in Ref's 3-5. Calibration and development was performed for 2-100 ft 70 mm and 3-100 ft 35 mm films exposed during 1977 (White Sands Missile Range - Sept. 1977).

PHOTOGRAPHIC SUPPORT TASKS

Darkroom procedures necessary to the efficient reduction and display of raw data and presentation of results were performed. Included were approximately 150 photographic prints utilized for star identification purposes (to determine camera orientations), visual inspection and choice of frames to be digitized for subsequent wind analysis (these prints also aid the operator of the digitizing system should his intervention be required). Some of these prints were also used for a supplementary star identification and calibration for the program Winter Anomaly (performed at Wallops Island in 1976). This

latter task identified the few stars which are present in the short duration exposures taken during the release as a check on the primary orientation calibration taken on the evening preceding the release. Additionally, periodic production of photographic slides, vu-graphs and prints of release frames, and of computer plots of reduced wind and shear was done for reporting to LKD project scientists and for presentation purposes.

Original photographic negatives are rarely used for digitizing stratospheric trail profiles for triangulation because of physical constraints of the automatic digitizing-reading system. It is hence necessary to make positive transparencies of the frames to be digitized. Extreme care must be exercised in producing these contact-printed transparencies since even minor spatial errors introduced from non-contact of the two emulsions during copying could degrade these high resolution measurements. Some 70 frames of the 1976 WSMR trail were copied in this manner for digitization. These transparencies were also carefully cleaned to ensure that no dust specks were copied which might adversely affect the automatic digitization process.

FIELD OPERATIONS

During the course of the program PhotoMetrics participated in the data-taking operation of one rocket release program, at White Sand Missile Range, NM in September 1977. Project goals were measurement of temperature, diffusion, and winds in the thermosphere from approximately 90 km to 180 km altitude.

PhotoMetrics' duties included participation in the final planning stages of the program, assisting LKD scientists in inspecting, testing and preparing for shipment of triangulation site photographic equipment, and setup and test of the optical and electronic equipment to be used at each of the two observation sites. Further work involved initial arrangements for communications with one site which was not located

within the missile range, operating one of the sites during the release, and aiding in preparing equipment for return shipment to AFGL.

The rocket was launched on 24 September 1977, following a one day delay because of poor weather. Although neither the rocket nor the TMA payload functioned completely as planned, it is still expected that usable data may be obtained from the photographic and other records of the release.

SECTION III

PROCEDURE DEVELOPMENT AND RESULTS

This section describes techniques used and problems encountered during triangulation and reduction of horizontal velocity components from digitized photographic records of trails.

THEORY OF TRIANGULATION TO TRAIL RELEASES

In principle, it is possible to uniquely determine the positions along a trail as a series of points in altitude, latitude and longitude from two photographic projections taken at nearly the same time from appropriately separated camera sites. Other information needed is latitude, longitude and altitude of the sites, time, and the camera parameters azimuth, elevation, focal length and horizontal tilt.

Numerous techniques have been employed in the past which utilize photographic methods to determine the location of tracer trails released in the atmosphere. Early attempts used plane geometrical solutions at very low altitudes. Later analyses for higher-altitude trails applied spherical geometrical methods, with corrections such as varying atmospheric refractive index and earth oblatness to improve the results. These latter procedures generally provided approximately 1/2 to 1 km vertical resolution and accuracies of 200-500 meters. References 8-10 are prepresentative of these approaches.

More recently, vector methods of solution were applied to this problem (Ref 1). If the assumption is made that site locations, camera parameters, and time are known within small error limits and photographs are digitized on a grid with reasonably small spatial separations, then these methods can provide high resolution positional solutions which allow horizontal velocity measurement in the stratosphere at 10 meter altitude increments. The procedure followed is to determine first the triangulation camera parameters utilizing the methods in Ref 2. This entails utilizing the known camera position,

the time of an exposure which records star positions, and the actual star positions (right ascension and declination, which may be calculated with extreme accuracy). Vector equations relating measured film plane coordinates of star images and the corresponding star locations may be solved to determine the orientation of the camera optic axis, the precise focal length of the lens, and the rotation about the optic axis needed for coincidence of the star field and its image. Atmospheric refraction and oblatness of the earth are included in the calculations. The above portion of the procedure is performed by LKD.

The triangulation procedure proper uses previously digitized film plane coordinates of a trail as seen from two sites, the site locations, and the camera orientations calculated from star calibration photographs. Vector methods of Reference 1 are utilized to calculate lines of sight for all trail points as seen from two of the triangulation sites. The intersections of a given point line of sight from the first site with several point lines of sight from the second site are calculated, and the separation vectors (nearest approach) of the lines of sight and the difference in dihedral angle of the planes generated by each line of sight and the line through the two sites are analyzed to produce a least error match of each film plane point from the first site with a corresponding film plane point from the second site. The position of each match in altitude, latitude, and longitude is calculated and stored for later use by a program which determines horizontal wind velocities from a time sequence of trail positions.

Several factors can and have adversely affected the results of the triangulation procedure. The major problem which has occurred with the first high resolution stratospheric trails (1973) is the inability to determine accurately the camera azimuth, elevation, and tilt at release time. The camera orientations at the moment the calibration frames were exposed are known, but at some time after the calibration and prior to the release, one or more of the cameras was inadvertently moved. A series of tests conducted by LKD in 1976 determined that

these motions could be caused by a very low force impact on the camera mount, probably when film magazines were removed and mounted, or if protective camera covers were used, during the covering or uncovering processes. Subsequently, further precautions have been taken to ensure that the cameras will not be moved after star calibration frames are exposed.

Another problem which may occur is that the time that the star calibration was exposed is not accurately known. Since the star positions relative to the observer are changing with time an error here will produce an error in the calculated camera orientation. For example, an error of one minute could alter one or more of the angles by as much as 1/4 degrees, depending of course upon the orientation of the camera (for a release 40 km distant this could result in an error of 175 m in position). This problem of operator error or misrecording of the time of star frame exposures, recognized after reduction of the 1976 Winter Anomaly data, was carefully guarded against in the 1977 measurements.

A logical difficulty appears in the actual algorithmic solution of the vector triangulation equations. Since each small "parcel" of trail cannot be uniquely identified in each of two views used, an iterative scheme to produce a "least error" identification must be employed. Results are critically dependent upon how this least error condition is chosen and upon limiting the area of search, since a particular line of sight may intersect the trail more than once.

ERROR ANALYSIS OF TRIANGULATION

Early in the program, several trails were reduced using LKD computer programs. The reduced wind profiles indicated probable errors existed in camera orientation or in the algorithms used for triangulation as evidenced by unusually large wind shears and spatial and velocity discontinuities appearing many times in the reduced data. Recalculation of camera angles was performed by LKD and produced only insignificant changes in these results. Since the present effort

is aimed at reducing pseudo-horizontal winds with no attempt to include possible vertical wind effects, the program was modified to reject any point match whose altitude was not higher than that of the previous match. At the same time the search for a matching point which could go both up or down through the trail point files was changed to search upward only, since for complicated trails allowing matching to proceed downward would eventually lead to the necessity of a long upward search and probable spatial discontinuity. The best match at this time was solely the smallest separation vector between lines of sight. Although results showed improvement over the previous ones it was felt that still further modifications were in order.

Several approaches were tried in conjunction with the separation vector as indicators of the best match. One of these, which involves projecting the chosen point from the first site into the film plane of the second site and calculating the radius from the projected point to the matched point, is still in use as an indicator of the accuracy of the matching and relates well to the quoted accuracy of the system used to digitize the trails. The most useful parameter however was found to be the dihedral angular mismatch between the planes generated by the two sites and the line of sight projections of the matched points. The primary matching criteria presently remain separation vector and angular mismatch.

Attempts to force an additional restriction of trail continuity worked well for frames at early times, but at late time when the trail has experienced considerable movement and shear from the wind field, the continuity length had to be made exceedingly large to prevent rejection of most of the trail points.

Further changes were primarily involved with the search procedures in an effort to speed the matching. In the same program area a tendency to weight the retention of a first-site point higher than the retention of a second-site point was eliminated.

As each of the above changes was applied, continuing improvement in the calculated wind profiles resulted. The final profiles still, however, contain more discontinuities than could reasonably be expected on the basis of the atmosphere's rapid damping-out of such extreme shears.

OPTIMIZATION OF CAMERA ORIENTATIONS

Comparison of wind profiles obtained from alternate site pairings when three triangulation sites were available again suggested errors in the camera orientation of one or more sites. Several methods were considered and some implemented in an effort to optimize the angles of one site by minimizing various error parameters while maintaining the angles of the other site.

It was found that automatic methods of minimization with no interactive guidance generally performed poorly. One semi-automatic method did perform well and was used on the Winter Anomaly data. The method depends upon having several "identifiable" features, in this case the end points of the trail. Triangulation is performed to these points, and each of the three parameters of the site to be optimized (azimuth, elevation, or tilt) is altered to obtain a minimum dihedral angular mismatch summed over all of the points used. Iteration on each of the three variables is performed, at each step substituting the newly determined angles from the previous step. The process is halted when it converges, that is when there is no longer a change in the dihedral mismatch.

Another, more laborious method, which could be made more automatic were there sufficient need for this type of analysis, was also used; it is judged to provide the most accurate optimization. Three triangulation sites are required and at least two identifiable features (preferably near the ends of the trail) must be present. Each of the three site pair triangulations are performed to each of the features, and inspection of the three sets of resultant coordinate data

(altitude, latitude, longitude) is made to determine the "most likely" of the 9 camera orientation parameters (3 per site) to alter to bring the sets of coordinate data into register. "Most likely" is that parameter which when changed will produce the largest improvement in the registration of the data. Because of the complexity of the scheme it was tested on only one of the oldest trails, and even then not carried to ultimate completion. As registration of the coordinate data is approached, changes needed in camera parameters become very small and choosing the "most likely" parameter to change must of necessity be programmed into an automatic process. As problems with orientation error are considered to be unlikely on any future trails, efforts to automate the process were deferred.

Since optimization to reduce errors in camera orientation when only two sites are available may cast doubt upon the final results, this procedure was used only as a last resort to recover data which would otherwise be lost.

VELOCITY ANALYSIS

Profiles of altitude, latitude, and longitude, for several times as input to this program are each converted to a uniform measurement system (meters altitude and meters north and east of a reference point). The data are then registered in altitude and the velocity components computed as least square fits of trail motion versus time. This least square analysis also provides convenient velocity error measurements.

An initial modification to this program was the addition of a cubic interpolator to place the input data on a uniformly spaced altitude grid. Elimination of wind discontinuities was also attempted in this program, the primary method used being calculation of partial velocities d_i/t_i for each altitude (d_i is the motion of the trail from time t_i to time t_{i+1}) and rejection of those velocities v_i, $i = 2, N$

which either exceeded a predetermined factor of v_1 or reversed sign from v_1. Only minor improvement could be noted and very few input points were discarded by this restriction.

The final change was made when it was noted that the cubic position interpolator was producing ringing (overshoot) effects. Substitution of a rather complex cubic spline interpolator not only reduced the ringing but at the same time practically eliminated the velocity discontinuities which had resisted all previous attempts at removal. Remaining discontinuities are correlated with sections of trail which have been deleted from the analysis since they appear to be experiencing downward motion.

RESULTS

Comparison of results for trails which allow alternate site pairing show excellent agreement. Errors in altitude registration between the two velocity determinations is most probably the result of inadvertent camera motion at one of the three sites. The structure correspondence of the two determinations is almost exactly repeatable as are the velocities themselves. In addition there is good agreement with Rawinsonde profiles usually taken several minutes before the trail release; total agreement with these in situ measurements should not be expected because of the time differential and the response time of this sensing device. Inspection of trail photographs also indicate qualitative correctness of the easterly velocity profiles. Present results indicate an altitude resolution of 10 meters for stratospheric trails with relative accuracy of 10-20 meters. Absolute altitude accuracy is less than 100 meters.

The fully modified procedure has been applied to three trails, Appolon and Flora (1973 stratospheric trails) and Winter Anomaly (1976 trail from 50 to 90 km). Representative data are shown for Appolon in Figs 1-5. Figure 1 is a plot of digital trail position, Figures 2 and 4 are velocity components determined by the smoke trail method, and Figures 3 and 5 are the component velocities derived from Rawinsonde tracking.

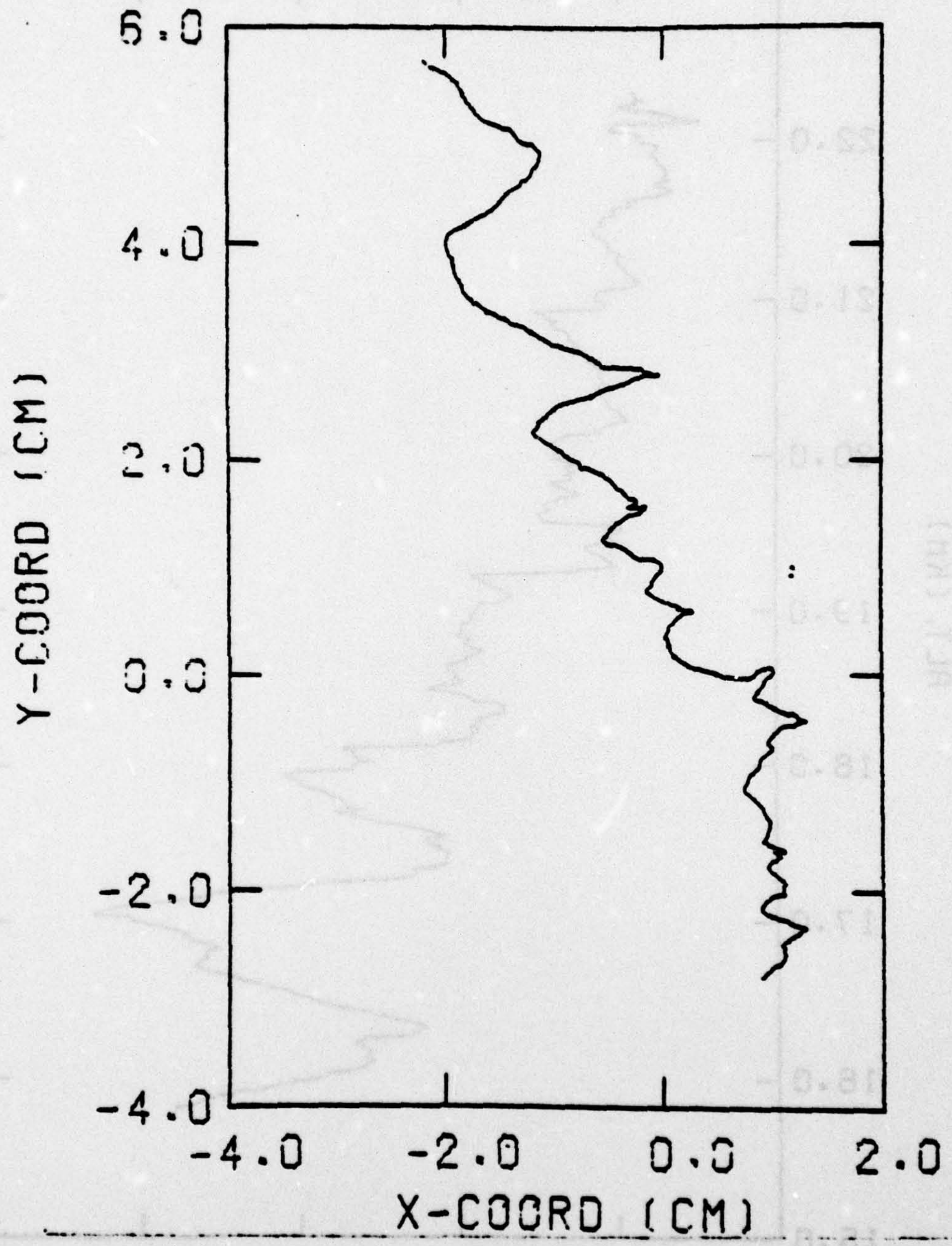

Figure 1. Computer plot of the digital film plane trail position for release Appolon as seen from Dona Ana site at t = 165 sec.

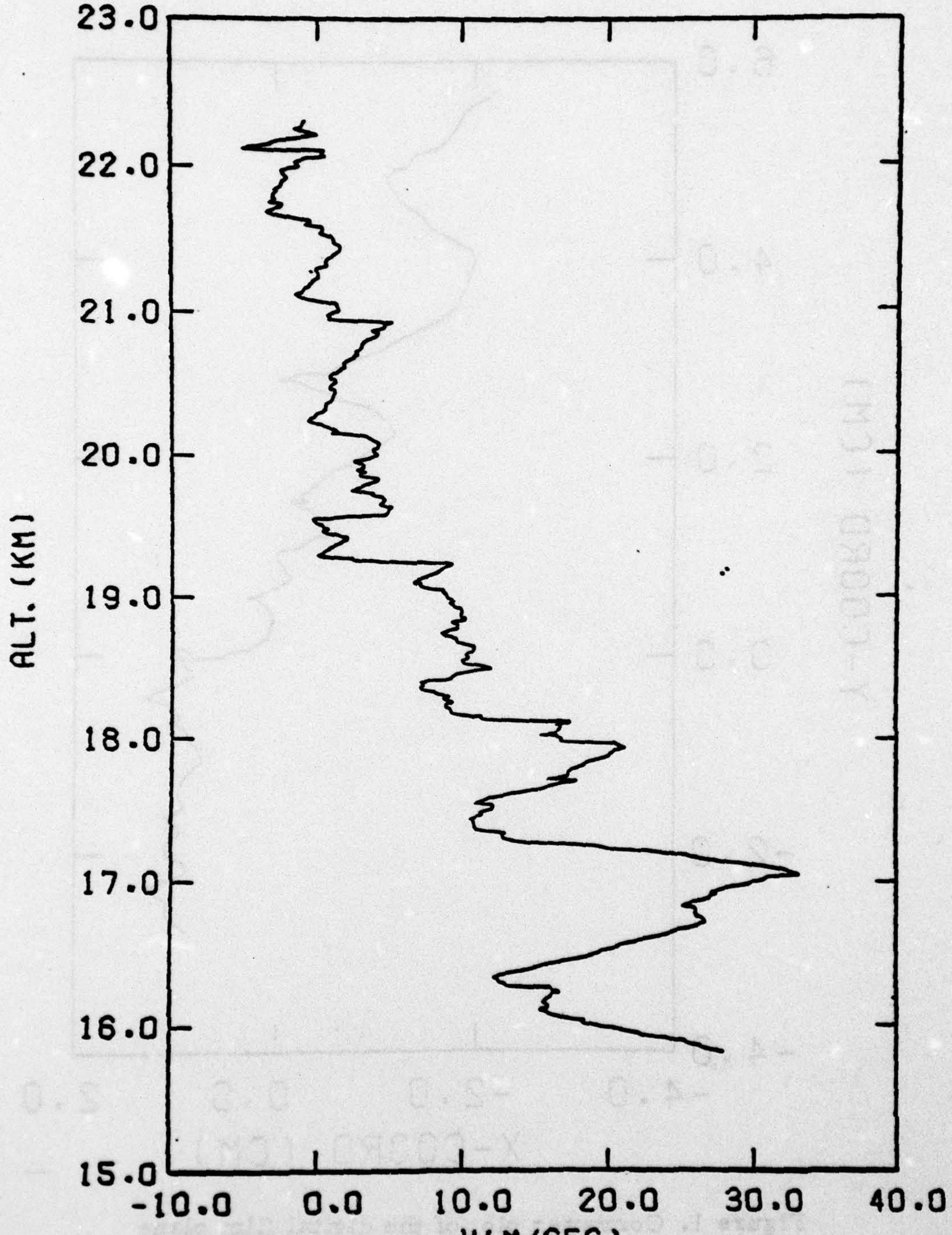

Figure 2. Easterly velocity profile determined from release Appolon by the smoke trail method.

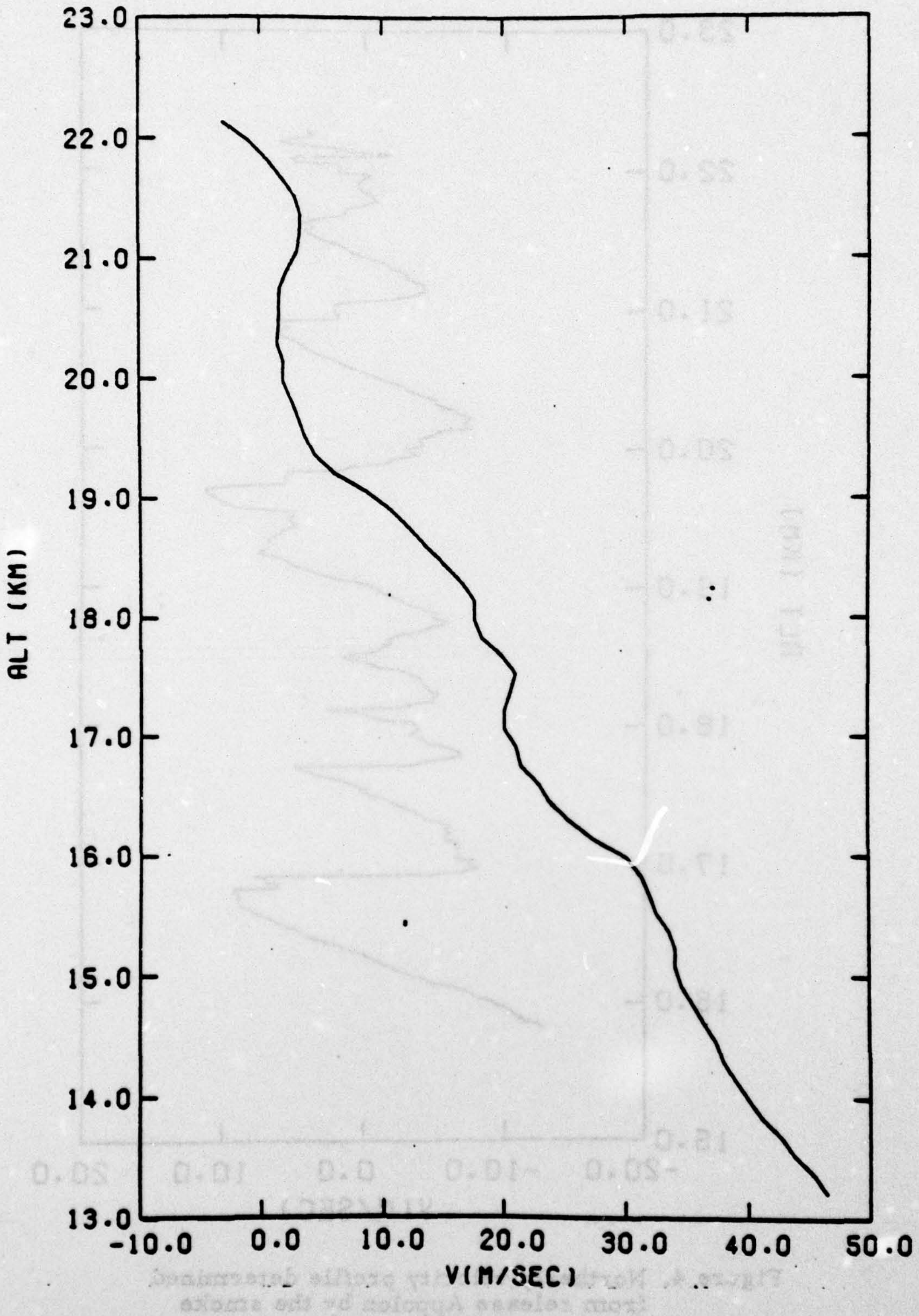

Figure 3. Easterly velocity profile at time of Appolon determined by rawinsonde tracking.

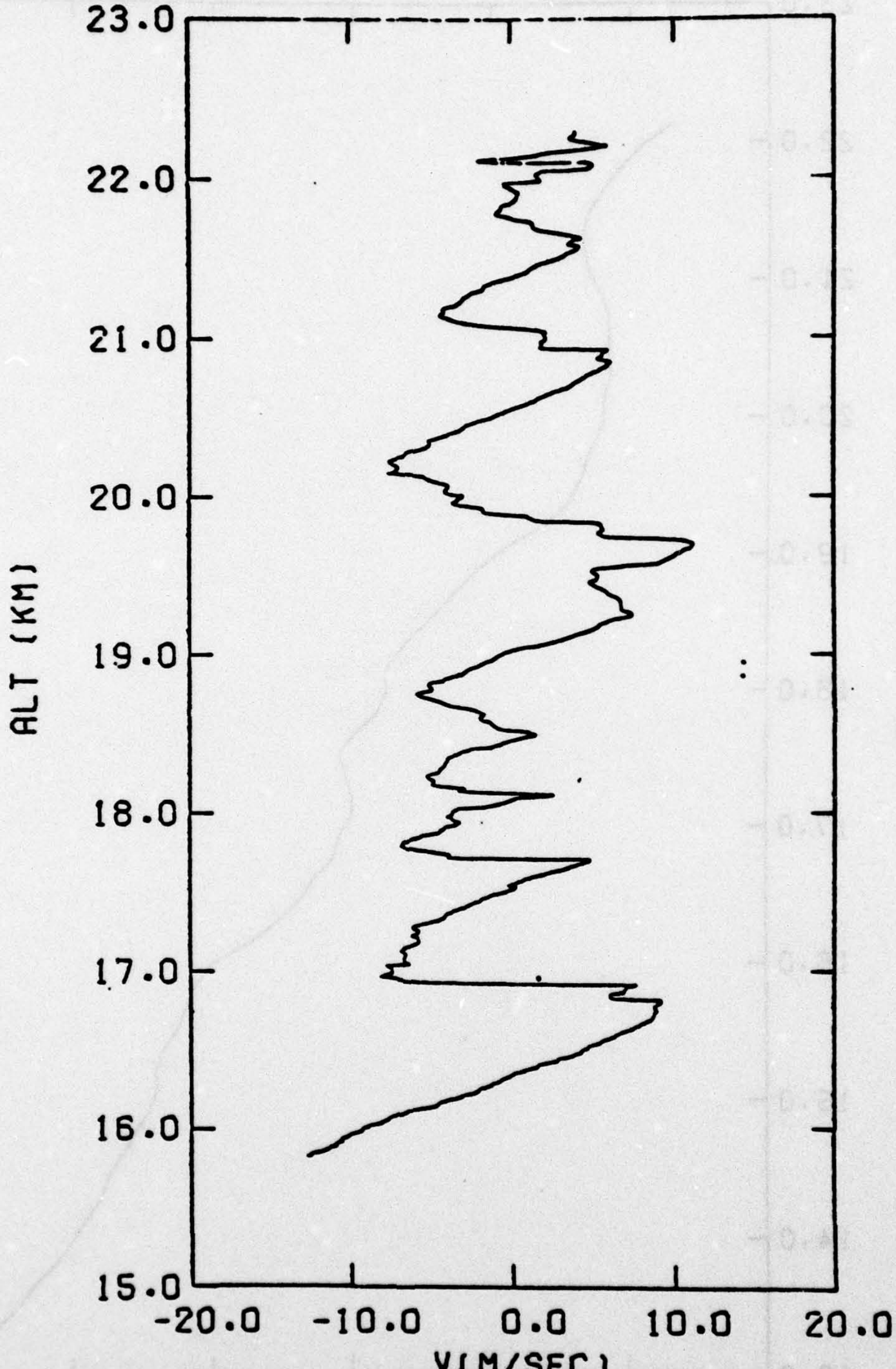

Figure 4. Northerly velocity profile determined from release Appolon by the smoke trail method.

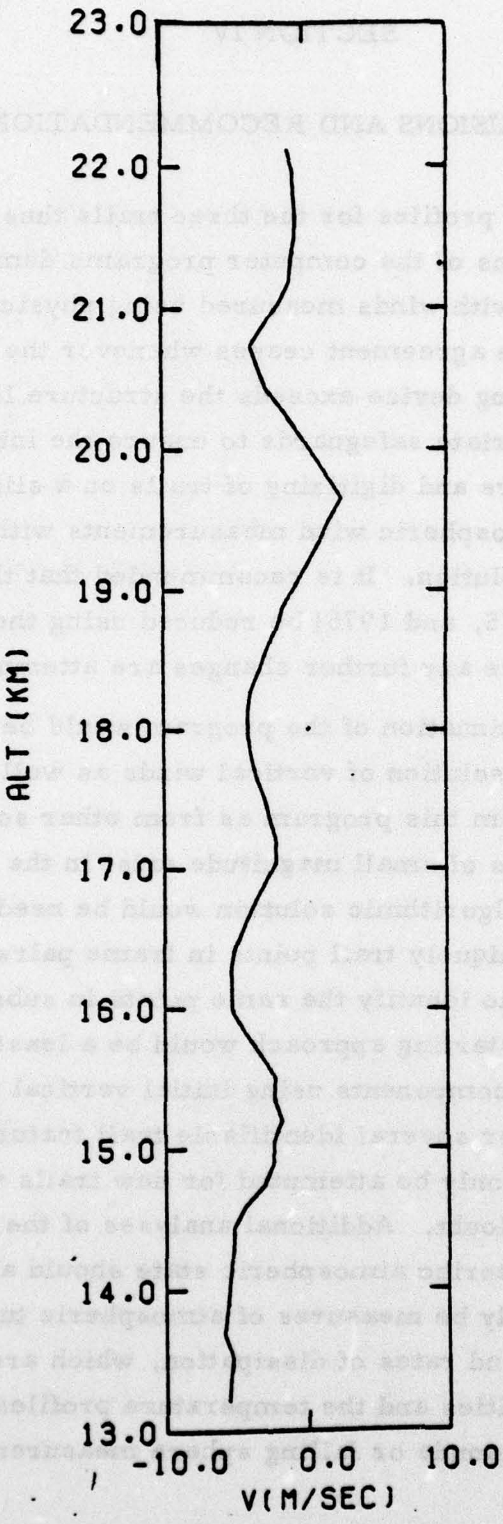

Figure 5. Northerly velocity profile at time of Appolon determined by rawinsonde tracking.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

Horizontal wind profiles for the three trails thus far reduced with the latest versions of the computer programs demonstrated excellent agreement with winds measured using physical, in situ sensing devices. The agreement ceases whenever the time constant of the direct measuring device exceeds the structure length of the fine scale winds. Appropriate safeguards to ensure the integrity of camera orientation parameters and digitizing of trails on a slightly finer grid should result in stratospheric wind measurements with approximately 5 meter vertical resolution. It is recommended that the remaining data (trails from 1973, 1975, and 1976) be reduced using the existing computer programs before any further changes are attempted.

An obvious continuation of the program would be extension of the solution to include resolution of vertical winds as well as horizontal. There is evidence from this program as from other sources that large scale vertical motions of small magnitude exist in the stratospheric region. A complex algorithmic solution would be needed which seeks not only to identify uniquely trail points in frame pairs taken at the same time, but also to identify the same points in subsequent frame pairs. An effective starting approach would be a least error resolution of the three velocity components using initial vertical motions which may be established for several identifiable trail features. Vertical wind analysis should only be attempted for new trails where camera orientation is not in doubt. Additional analyses of the photographic image data to characterize atmospheric state should also be considered. These would primarily be measures of atmospheric turbulence such as Richardson number and rates of dissipation, which are calculable using the determined velocities and the temperature profiles which are available from Rawinsonde or falling sphere measurements.

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